**The Thesis Committee for Melissa Marie Lewis**
**Certifies that this is the approved version of the following thesis:**

# Effects of Varying Force Levels and Combinations of Force Application and Release During an Isometric Pinch Force Task

**APPROVED BY**
**SUPERVISING COMMITTEE:**

**Supervisor:** ______________________________
Lawrence Abraham

______________________________
Jody Jensen

# Effects of Varying Force Levels and Combinations of Force Application and Release During an Isometric Pinch Force Task

**by**

**Melissa Marie Lewis, B.S.**

**Thesis**

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

**Master of Science in Kinesiology**

**The University of Texas at Austin**

**August 2014**

# Abstract

## Effects of Varying Force Levels and Combinations of Force Application and Release During an Isometric Pinch Force Task

Melissa Marie Lewis, M.S. Kin
The University of Texas at Austin, 2014

Supervisor: Lawrence Abraham

Fine motor control is important for the completion of many activities of daily living, such as writing, eating, buttoning a shirt, and texting. All these tasks require a high amount of continuous coordination and regulation of increasing and decreasing forces between multiple digits using sub-maximal force levels to successfully accomplish the task. Thus understanding the coordination of force regulation by the thumb and index finger at these sub-maximal force levels is a relevant topic especially for rehabilitation and instrumentation. This study was designed to investigate how accuracy and smoothness of performance of an isometric pinch force tracking task is affected by changing the level of forces required to perform the task and by different combinations of application and release of force by the thumb and index finger. Twenty two healthy, right handed adult participants between the ages of 18-30 were asked to manipulate a cursor to track a moving target ball counterclockwise around a prescribed path using the thumb and index finger of the right hand only. The goal of the task was to keep the cursor as close as possible to the moving target throughout the entire trial. Each participant was given 50 practice trials: 25 at 24% MVC and 25 at 12% MVC. For the 40 experimental trials, participants returned 24 hours later to complete 10 trials at each of the following force levels: 4%, 8%, 16%, and 32%. RMSE and CVE were calculated for each digit (thumb and index finger) as well as the combined digits and were used as indicators of accuracy and smoothness, respectively. Results showed significant differences in all dependent variables with p-values less than 0.05. Task performance accuracy was found to decrease as force level increased, whereas smoothness was found to decrease as force level decreased for all three. These findings suggest that varying force levels and combinations of force application and force release can change performance of this fine motor task and should be further investigated in order to better understand mechanisms involved and for implementing new designs of equipment and diagnostic tools.

# Table of Contents

## List of Figures

# Chapter 1: Introduction

Force control and production has been a topic of many studies throughout the years in the scientific world. Studies range from those examining the action of large muscle groups to those assessing single unit muscle firing and include examination of fine motor control. Fine motor control is important for the completion of many activities of daily living. Activities of daily living (ADLs) that include fine motor control include, but are not limited to: writing, eating, buttoning a shirt, and texting. All these tasks require a high amount of continuous coordination and regulation of increasing and decreasing forces between multiple digits using sub-maximal force levels to successfully accomplish the task. Thus understanding the coordination of force regulation by the thumb and fingers at these sub-maximal force levels is a relevant topic, especially for rehabilitation following injury as well as creating better instruments to assist with activities of daily living. This study was designed to investigate how accuracy and consistency of performance of an isometric pinch force task is affected by changing the level of forces required to perform the task and by different combinations of application and release of force by the thumb and index finger. The results of this study will expand the knowledge of factors that affect the accuracy and coordination of force regulation by the thumb and index finger.

In previous research, many studies have been completed examining the relationship between force level and accuracy by different finger force task. Lindberg et. al. (2008) reported visuomotor tracking was more demanding at low force levels when analyzing whole group data independent of age. Masumoto and Inui (2010) also reported that participants had more difficulty in decreasing force to achieve target force at lower force levels than to increase force to meet the same target force level. This study used only a right index finger tapping task with force levels ranging from 5%-40% maximal voluntary contraction (MVC), and an auditory metronome was used to adjust the pressing rate. Another study finding similar results was Harbst et. al (2000), using cyclical increases and decreases of force ranging from 10%-40% MVC, which resulted in less variability in performance when increasing force to match low force level targets than high force level targets. This study also found larger constant error occurred at the lower force levels than at higher force levels.

Limitations of these studies include measurements of only total combined force of both fingers during the bimanual pinch task (Harbst, et. al, 200) and only the index finger force in Masumoto and Inui (2010). Only measuring total force prevents the understanding of how the individual digits are coordinated to regulate force control and variability, whereas only using the index finger confines the generalization to only some activities of daily living, because ADLs usually require the coordination of more than one digit at the same time. These studies also limited the amount of visual feedback given throughout practice trials and test trials. This adds an extra component of memory to be able to match the minimum and maximum force levels. In this study, visual feedback was given throughout all practice and test trials in order to focus solely on accuracy and consistency of force control. Finally the previous studies used a single level of force production throughout the matching task, not a task with continuously changing levels of force production. These are known as dynamic isometric tasks and this study we employed a tracking task which applied force levels ranging from 5%-20% MVC in order to navigate around the template.

Studies utilizing this type of dynamic isometric task have involved tracking a sine wave shape while plotting force over time (Knight and Kamen, 2007; Moerchen et. al, 2007; Vaillancourt and Newell, 2003) or tracing a 45 degree straight line plotting y-axis directional force against the x-axis directional force (Francis et. al, 2012; Spirduso et. al, 2005; Kamen and Du, 2000). In order to perform these tasks, participants were compelled to adjust the applied force throughout the entire task to track the target line. The task used in the present study would be considered similar to the tasks found in the above studies, but with more complex adjustments and coordination of force application and release by the digits and with the constant of tracking a moving target along the line.

Many studies have found results suggesting high force variability, measured using the coefficient of variation (CV), occurs in tasks requiring low force level production. This variability has also been shown as an inverted U-shape relationship with force levels (Danion and Gallea, 2004; Taylor, Christou, & Enoka, 2003). However, other studies have found different results, with variability being the same across all force levels for young participants (Ranganathan et. al, 2001). In the present study, the coefficient of variation of error (CVE) was used to measure variability or smoothness of performance.

Literature concerning various combinations of force application and release in finger coordination is not as numerous as the force control literature. A study involving force application and release in finger coordination examined the different combinations of force in a tracing task around a triangle template (Spirduso and Choi, 1993). During this study, side one of the triangle required forces applied to both levers to be simultaneously increased in the same direction while side two and side three required opposite force application and release of the two digits. The results indicated that accuracy, as assessed by root mean square error (RMSE), was lower for side one than for either of the other two sides while side two had the highest amount of error. Side one was found to be the easiest for the participants to trace (task performance was most accurate when both digits were applying force in same direction), while when the digits were modulating force production in opposite directions the task was more difficult, resulting in a decrease in accuracy.

With all that known, research investigating simultaneously the effects on accuracy and consistency of different force levels and different combinations of forces between digits has not been reported for an isometric pinch force tracking task. The goals of this study were to compare task performance accuracy and consistency among various patterns of force combinations at four different magnitudes of force (% MVC) in both thumb and index finger in a pinch force tracking task. The data were analyzed to test the null hypothesis that for the pinch force task there would be no differences in accuracy or consistency of task performance among the different force levels. Similarlyly, we also hypothesized there would be no differences in accuracy or consistency of task performance among the various combinations of force application and release.

# Chapter 2: Methods

## 2.1 PARTICIPANTS

Twenty-two adult volunteers (twelve men and ten women; mean age ± SD, 25.7±3.2) participated in this study. To be eligible for participation in this study, individuals must have been between the ages of 18 and 30 years, been right-handed, and reported no neurological or vision disorders. Also participants must have not been medically diagnosed or treated for any serious injury to the right arm or hand as well as having no previous experience with the experimental apparatus used in this study. Individuals not meeting these criteria were immediately excluded from this study.

## 2.2 TASK AND PROCEDURES

This study used the manual force quantification system (MFQS) apparatus in order to quantify the low-level isometric forces from the thumb and index finger in a precision pinching task through two independent force transducers (Spirduso et al, 2005). A computer screen provided the visual display and feedback of the task being performed by each participant as manipulation of the position of a cursor ball on the screen occurred. This position of the cursor ball was directly associated with the amount of force produced by the thumb and index finger respectively. The thumb force determined the X-axis values of the cursor position and the index force determined the Y-axis values with force increases causing cursor movement in the positive direction and force decreases causing cursor movement in the negative direction. The participant was seated in a chair facing the computer screen with the right arm flexed at 135 degrees at the elbow. A strap was used for immobilization of the participant's right forearm and elbow with the hand extended as the thumb and index finger rested on the force transducers. The width between the two force transducers always remained at a constant two inches while the height of the chair and location of the force transducers could be adjusted based on the height and arm-hand geometry of the participant. The orientation of the force transducers was also adjusted to encourage the participant to touch the respective transducer pads with only the thumb and index finger while the three unused digits were loosely flexed into the palm. Immobilization of the force transducer apparatus was achieved using a magnetic clamp on a metal plate. Therefore, this equipment allowed measurements of independent isometric flexion, or pinch force, of each digit without any motion of the participant's hand or arm.

A maximal voluntary contraction (MVC) force level for each digit was measured initially using a 20-pound maximum pinch transducer. This MVC was used to establish the target force levels for that day's practice or experimental trials; each day a new MVC was recorded. During the single MVC trial each day the participant was asked to apply as much force as possible with both thumb and index finger on the transducers for three-four seconds. Each participant was then tested on the experimental task at 4%, 8%, 16%, and 32% of MVC. All experimental trials were conducted using a10-lb transducer in order to insure more sensitivity during data collection.

The goal of this isometric pinching task was to guide the participant-controlled cursor ball around a diamond shaped tracking template following a moving target ball from the start point to the finish point (see Figure 1). In all trials, four different combinations of force applications and release were tested. Data were collected from these conditions from all participants (Figure 1, red arrows): 1. Both thumb and index finger forces decreasing (release) 2. Thumb force increasing (application) and index finger force decreasing (release) 3. Both thumb and index finger forces increasing (application) 4. Thumb force decreasing (release) and index finger force increasing (application). The participant was instructed to keep the cursor ball on or as close as possible to the moving target ball that moved steadily counterclockwise around the prescribed shape for twenty-eight seconds at four different force levels. This study required two days of participant involvement, with day one including the practice session consisting of fifty practice trials at 24% or 12% MVC. The practice trials were completed by all participants in the following order: 10 trials at 24%MVC, 10 trials at 12% MVC, 15 trials at 24%, and 15 trials at 12% MVC for a grand total of 25 trials at 24% and 25 trials at 12% MVC. Day two testing began 24 hours after the practice session and was comprised of test trials conducted at 4%, 8%, 16%, and 32% MVC with 10 trials performed at each force level for a total of forty total test trials. The order of force levels tested on the second day was randomly assigned to every individual among the 22 participants, with a different order assigned to each participant such that 22 of the 24 possible category pattern orders were represented. For both days, rest periods of twenty seconds between trials and sixty seconds between sets of 10 trials were given to minimize fatigue effects. Only the data collected from the test trials on day two were used for analysis.

On the first day, an explanation of the procedure and a consent form were provided to the participants upon arrival. Consent was obtained, any questions were answered, the MVC test protocol was performed, and all the practice trials were completed. On day two, the experimenter provided a review of procedures and how the equipment was operated, a new MVC test protocol was performed, and all test trials were completed.

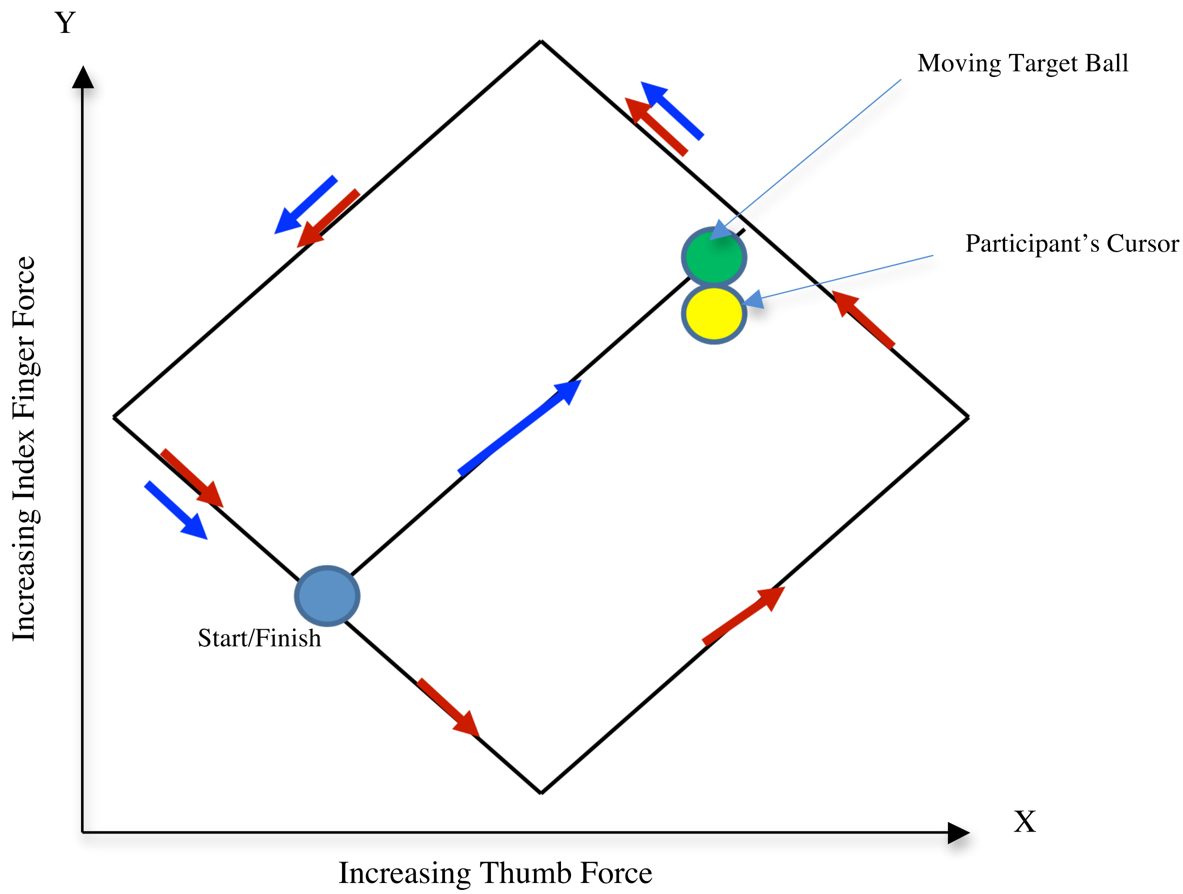


Figure 1: Diamond shaped tracking template in which the thumb manipulates the x position of the cursor (the yellow ball) and the index finger manipulates the movement of cursor in the *y* direction on the reference frame. Blue arrows indicate movement of the target ball around segments not analyzed while red arrows indicate movement of the target ball around segments being analyzed. The position of cursor reflects the combined force exerted by the individual digits. The green ball is the target ball, which moves at a constant speed counterclockwise around the prescribed path. Testing occurred with the full screen scaled to four different force levels: 4%, 8%, 16%, and 32%.

**2.3 DATA ACQUISITION**

All data were collected in the Motor Behavior Laboratory, located on the 8$^{th}$ floor of Bellmont Hall at The University of Texas at Austin campus, using the MFQS apparatus. This apparatus included a Dell computer, a 14-inch LCD screen, custom-designed LabVIEW software, and a pair of isometric force transducers with an A/D converter. LabVIEW software was used to display the task and instructions, to sample data, and to store the data for offline analysis. Two pairs of strain-gauge sensors recorded all pinch forces performed, with the maximal pinch forces (MVF) measured using sensors calibrated up to 20 lb of force and sensors calibrated up to 10 lb force used for all other testing and practice trials for greater precision. Force data were sampled at 1000Hz with a LabVIEW application which then averaged every set of five consecutive samplings to create force data with a sampling rate of 200Hz.

**2.4 DATA ANALYSIS**

In order to compare the four different combinations of force exertion and four different force levels, the diamond shaped path analyzed was divided into eight segments, each representing changing combinations of force application and force release by the thumb and index finger respectively. Data from the first two segments were not analyzed because they functioned as a "warm up" phase for each trial. Also the last two segments were not analyzed, as they were repeated segments in order to end the trial at the starting point. Segments 2 and 7 also functioned to provide for equivalent initial and final conditions for all four test segments (begin and end with a change in direction). All segments were completed in numerical order with segment three consisting of both the thumb and index finger releasing force, segment four consisted of thumb application and index finger releasing, segment five required both application of force with the thumb and index finger, and segment six used release with the thumb and application with the index finger (See Figure 2). Two dependent variables were calculated to determine accuracy and smoothness of task performance for all four combinations of application and release at each of the four force levels for combined thumb and index finger, only thumb, and only the index finger.

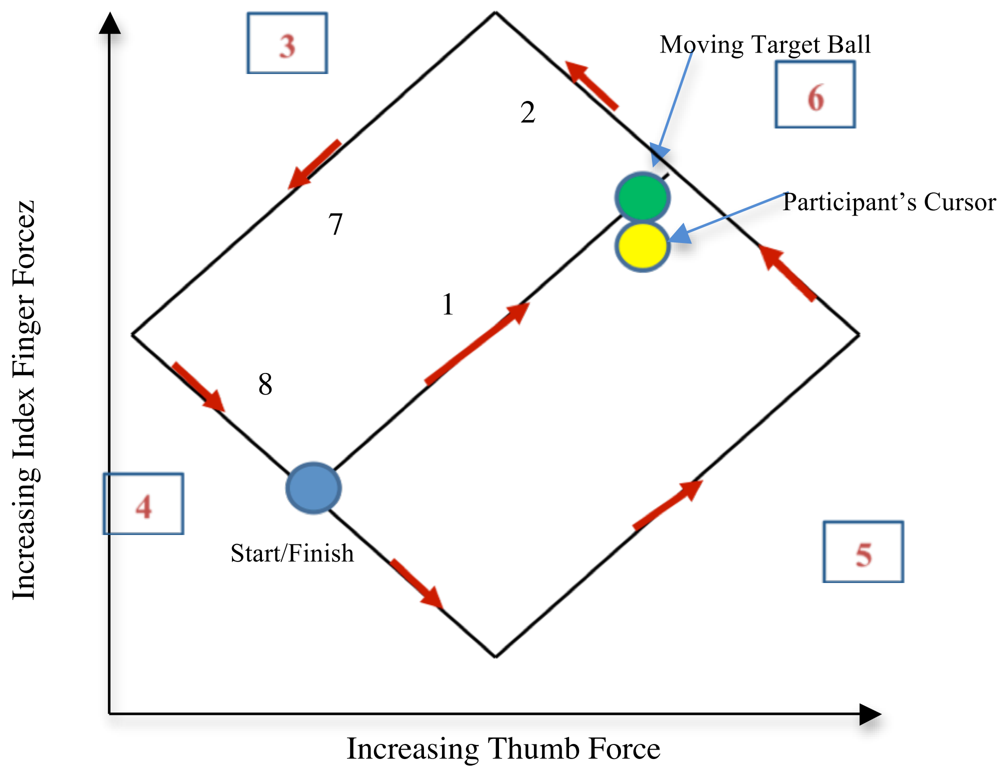


Figure 2: Segments for diamond shape tracking template. Segment 3 was performed by both thumb and index finger releasing force, segment 4 was performed by the thumb applying force and index finger releasing force, segment 5 was performed by both thumb and index finger applying force, and segment 6 was performed by the thumb releasing force and the index finger applying force

Root mean square error (RMSE) was calculated to evaluate the average instantaneous accuracy of the tracking performance. RMSE was determined as the square root mean of the squared distance between the cursor and the track ball for each sample and then converted into %MVC. RMSE reflected the horizontal or vertical error distance for the thumb or index finger, respectively, and the direct diagonal distance for the combined data.

Smoothness of the performance was measured as the coefficient of variation in the magnitude of error (CVE) across all combinations of application and release as well as for all force levels. CVE was the measurement of smoothness of the tracking performance, so higher values indicated less smooth or more erratic motion of the participant-controlled cursor.

The cursor position data collected from each test trial were processed with MATLAB and Excel programs to determine RMSE and CVE for each force level and each segment for all 40-test trials per participant. A coding system was used on all participant records to ensure confidentiality and anonymity in regards to the identity and performance of all participants.

Six separate statistical analyses were used for testing task performance for each of the six dependent variables. For the four force levels, as well as the four segments representing the different combinations of force exertion, 4x4 analysis of variance (ANOVA) tests were performed for combined RMSE, combined CVE, thumb RMSE, thumb CVE, index finger RMSE, and index finger CVE. Whenever significant main effects were found, Bonferroni post hoc tests were used to further examine the significance of differences between force levels or combinations of application/release. SPSS was used for all statistical comparisons and the level of significance was set to $p < 0.05$.

# Chapter 3: Results

The main effect of force levels on tracing accuracy was found to be significant for thumb RMSE ($F(3,22)= 96.156$ , $p<0.05$), index finger RMSE ($F(3,22)= 163.094$, $p<0.05$), and the combined thumb and index finger RMSE ($F(3,22)= 34.433$, $p<0.05$). Figure 3 displays the combined thumb and index finger RMSE measured in percent MVC at each force level. These results suggested that in general as force level increased, RMSE increased, meaning that for combined thumb and index finger RMSE as force level increased, accuracy decreased. However Bonferroni post hoc analysis revealed the significant differences ($p< 0.05$) were only between the three lower force levels (4%, 8%, 16%) and the highest level (32%). Thus for the combined pinch force accuracy, this effect of decreased accuracy was only found at the highest force level.

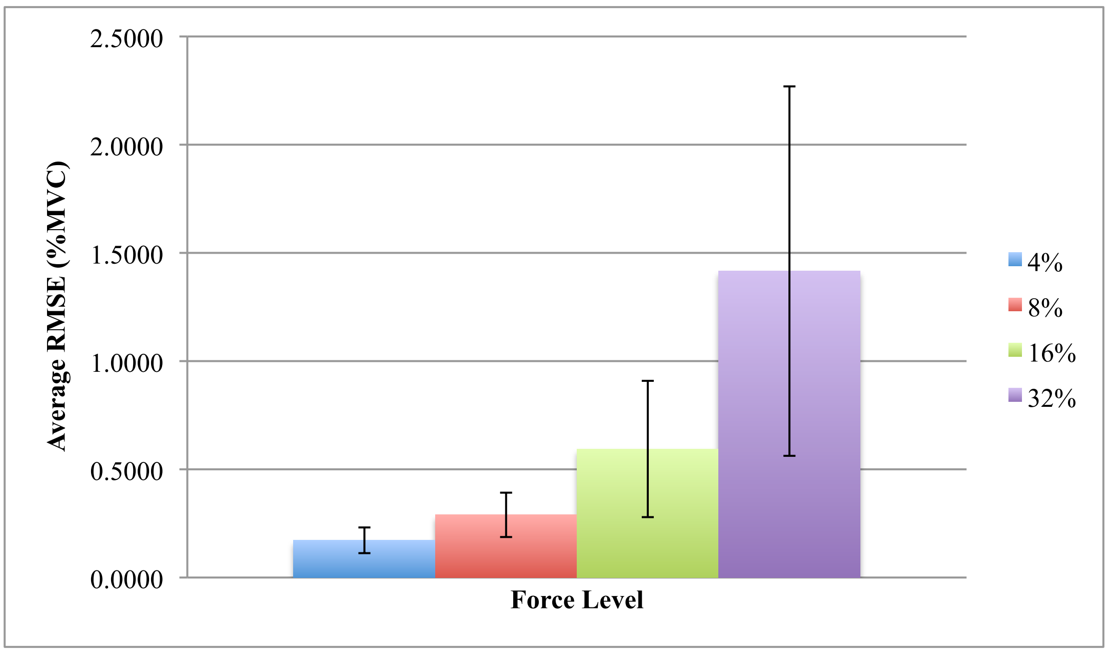


Figure 3: Combined Thumb and Index Finger RMSE by Force Level

Figure 4 displays the thumb RMSE measured in percent MVC at each force level. Following a similar pattern to that of the combined thumb and index finger RMSE, as force level increased, RMSE increased too. However the post hoc tests revealed significant differences ($p< 0.05$) between the 4% force level and both 16% and 32% as well as between the 8% force level and both 16% and 32%. So for the thumb alone, accuracy decreased as force level increased across almost all force levels.

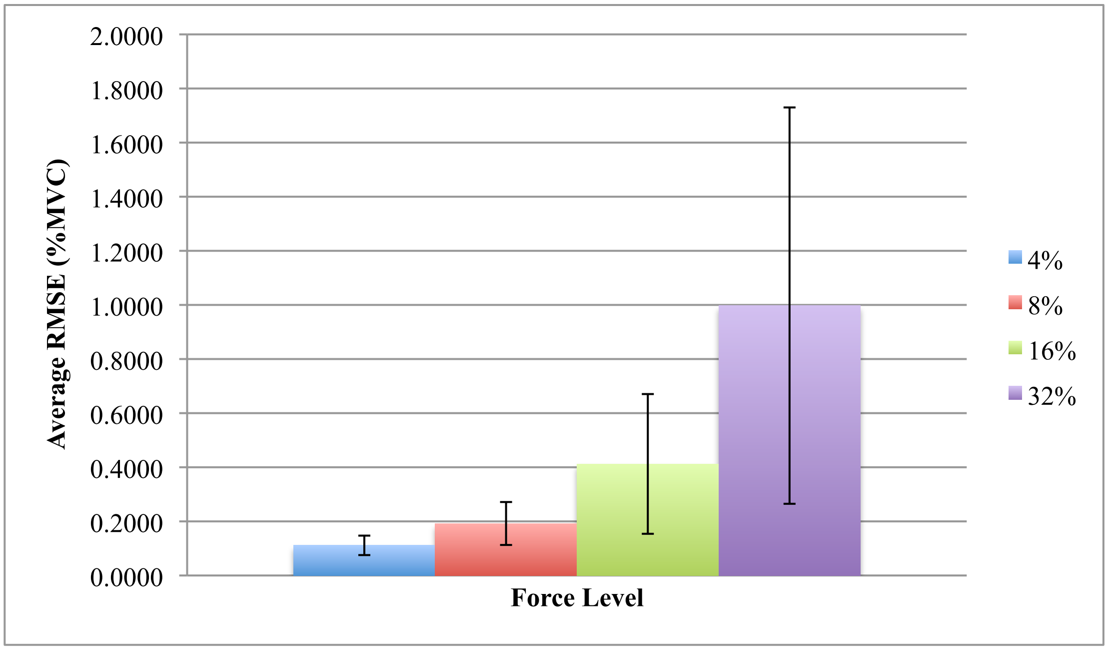


Figure 4: Thumb RMSE by Force Level

Figure 5 shows the index finger RMSE measured as percent MVC at each force level. Again following the tendencies found in both thumb RMSE and Combined thumb and index finger RMSE, as force level increased, so accuracy decreased (increased RMSE). The post hoc tests revealed significant differences ($p < 0.05$) between the 4% and 8% force levels and the 16% and 32% force levels.

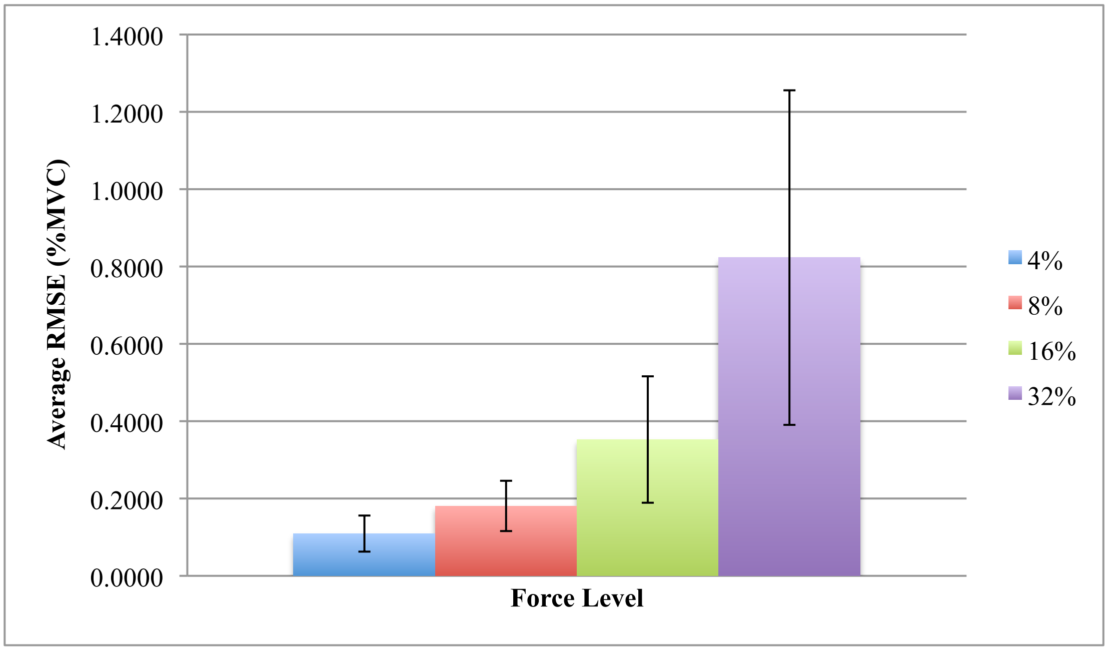

Figure 5: Index Finger RMSE by force level

A significant main effect for RMSE by segment was only found in the thumb. Post hoc results determined the significant differences ($p<0.05$) were between segments 4 (thumb application/index finger release) and 5 (thumb application/index finger application). Figure 6 shows thumb RMSE divided up by the different combinations of force application and release and force level within each combination. Figure 7 displays accuracy measured by RMSE in the thumb when the digits were completing segments in which the thumb and index finger were using the same direction of force exertion (thumb release/index finger release or thumb application and index finger application) vs when the digits were completing opposite combinations of force exertion (thumb application/index finger release or thumb release and index finger application).

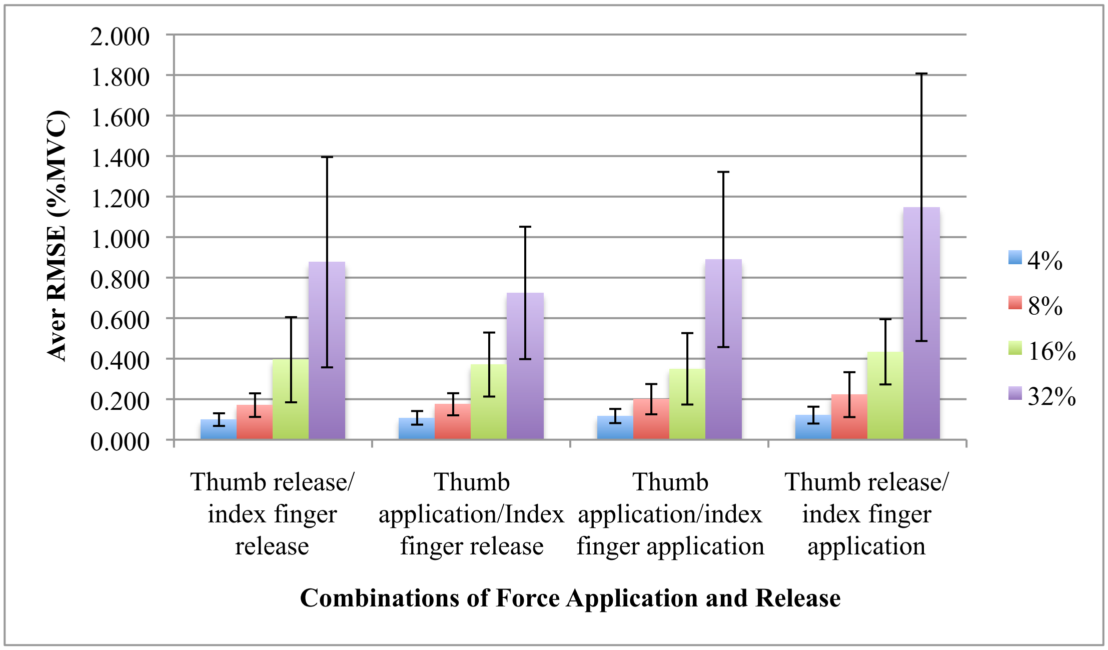


Figure 6: Thumb RMSE by Segment

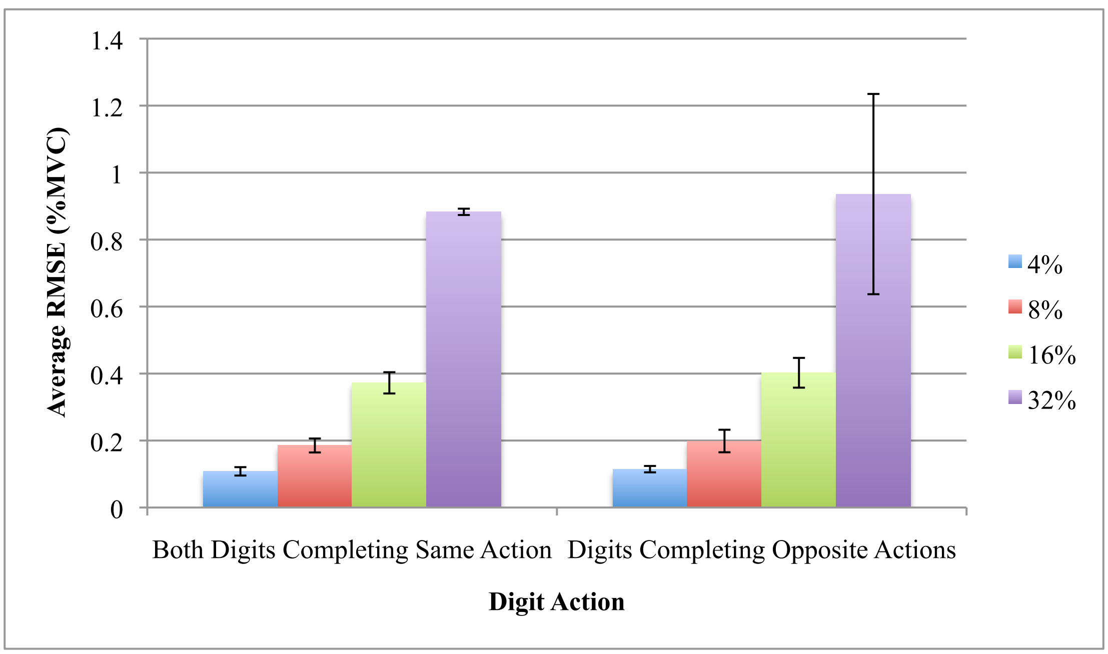


Figure 7: Thumb RMSE by Digit Action

Significant main effects were found in CVE by force level in data from thumb CVE ($F(3,22)= 7.795$ $p<0.05$), index finger CVE ($F(3,22)= 6.377$ $p<0.05$), and combined thumb and index finger CVE ($F(3,22)= 9.831$ $p<0.05$). Main effects were also found in

CVE by segment for thumb CVE (F(3,22)= 26.249 $p<0.05$) and combined thumb and index finger (F(3,22)= 13.001 $p<0.05$). Post hoc tests for combined thumb and index finger CVE revealed significant differences to be between all lower force levels (4%, 8%, 16%) and 32% (see figure 8). These tests also showed segment significant differences in segment 3 compared with 5 and 6, segment 4 compared with segment 6 (see figure 9). Overall the CVE for the combined digits was higher at lower force levels meaning that the lower the force level the less smooth or more erratic was task performance.

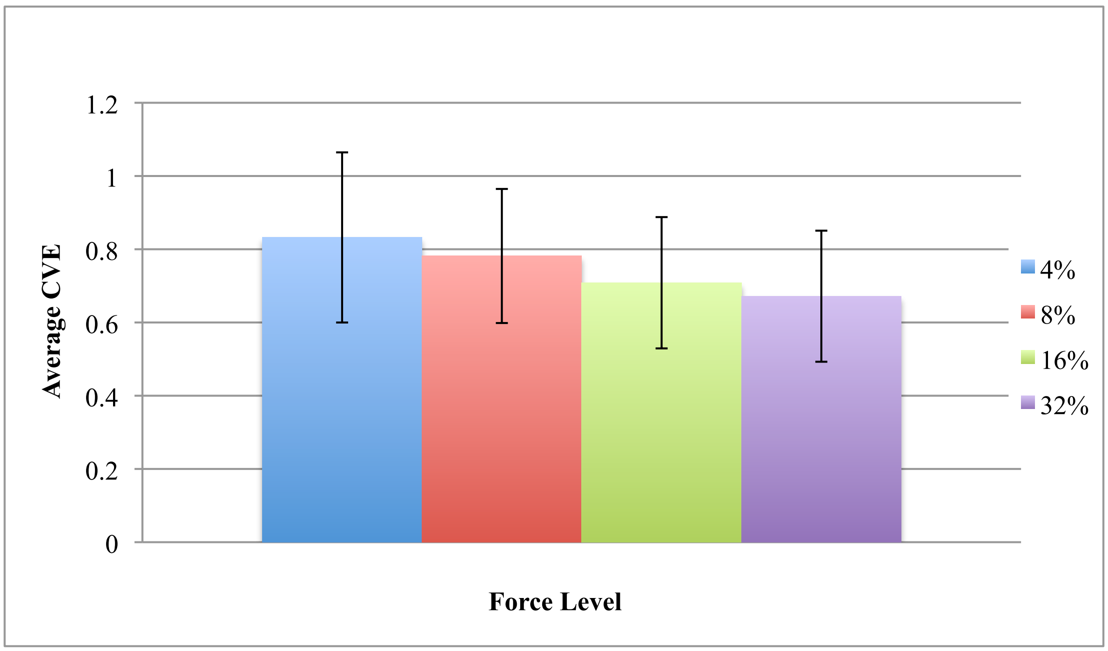


Figure 8: Combined Thumb and Index Finger CVE by Force Level

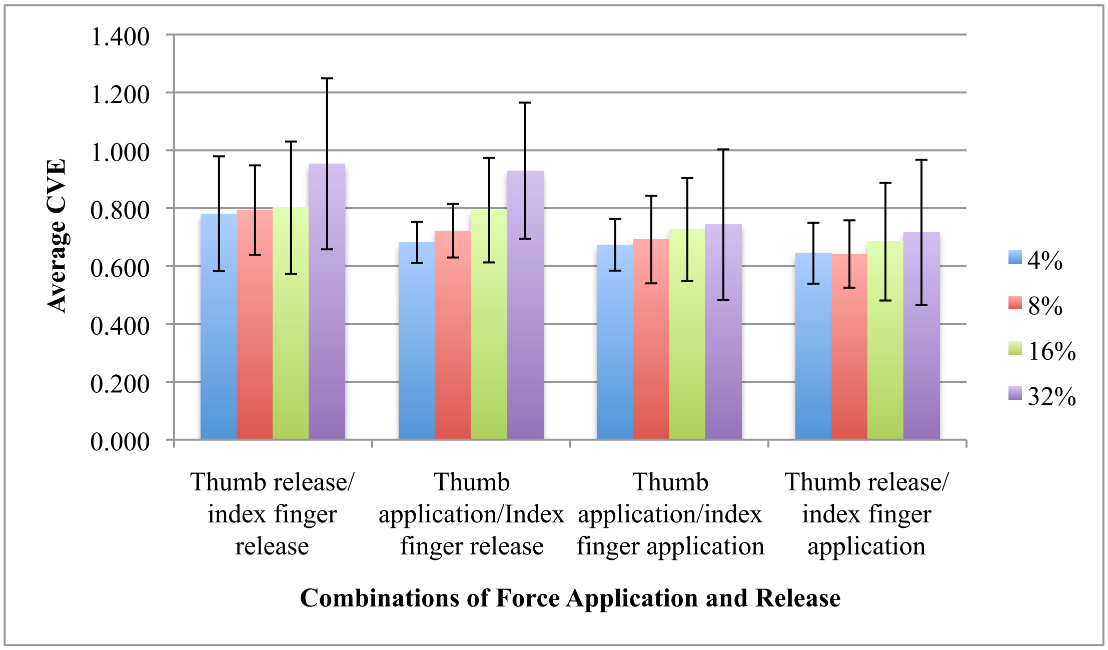


Figure 9: Combined Thumb and Index Finger CVE by Segment

Post hoc tests for thumb CVE revealed significant differences for all lower force levels (4%, 8%, 16%) compared with 32% (see figure 11) as well as significant differences in segments 3 and 4 compared with segments 5 and 6 (see figure 12).

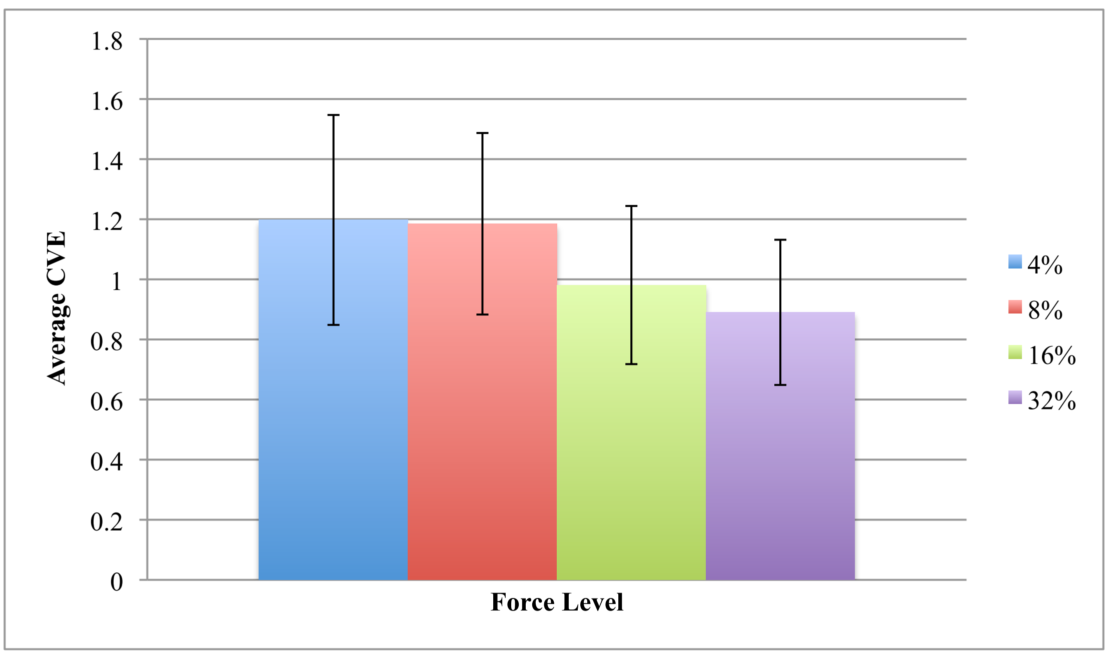


Figure 10: Thumb CVE by force levels

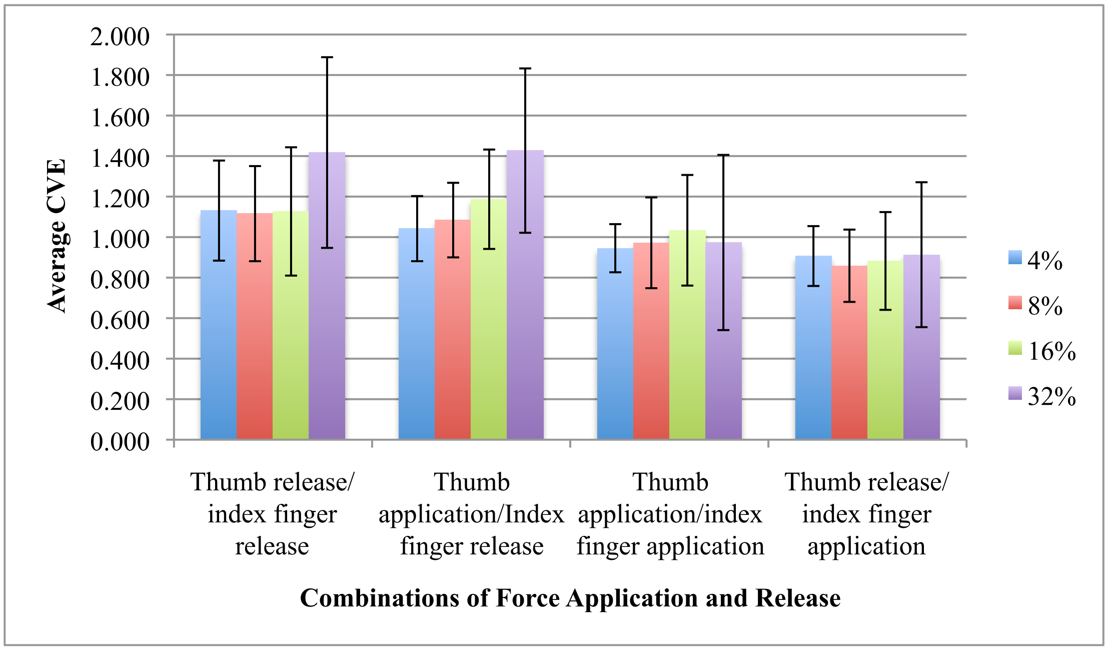


Figure 11: Thumb CVE by Segment

Post hoc tests for index finger CVE showed significant differences for both 4% and 8% compared with 32% (see figure 13).

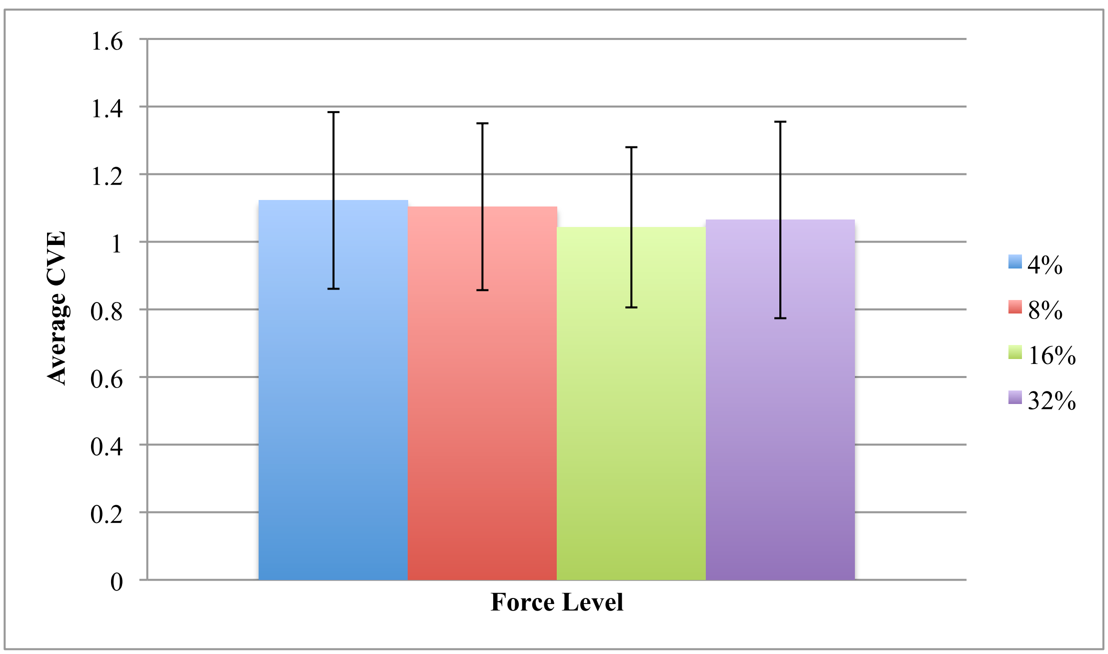


Figure 12: Index Finger CVE by Force Level

# Chapter 4: Discussion

The findings of statistically significant effects of force levels and task segment on accuracy and smoothness in both digits as well as in the combined digits suggest a very complex set of interactions. However, careful examination of the results reveals support for previous literature as well as some unique findings.

Error has always been one of the most common dependent variables to measure accuracy of performance. In this study, the general tendency for both digits was that as force level increased, error also increased. This was consistent with a study by Slobounov, Johnston, & Ray in 2002 in which error was shown to increase as a function of the increasing force levels. That study also reported evidence that force production at low levels is more challenging than at high force levels. This phenomenon was also supported by the data from this study, since significant differences were found between the low force levels and the highest force level, and is consistent with the findings from previous studies by Harbst et. al (2000) and Masumoto et al., (2010). Finger accuracy has been shown to have more error when releasing force than during force application without respect to the force level (Lingberg et. Al, (2009). In this study, the index finger often exhibited the greatest error when releasing (decreasing) force, either because it was to trying to match a low force level or perhaps because a difficult horizontal action of the finger was being used to bring the cursor vertically down the screen.

Another main finding of this study was that smoothness was better at higher force levels than at lower levels of force, which supports previous literature reporting multi digit force regulation and coordination at low levels of force (Slifkin and Newell, 2000).

A few limitations to this study should be recognized. One limitation is the sample size. There was a large amount of variability as the force level increased and this variability could have been due in part to the small sample size. Another limitation was not completely ruling out fatigue as a cause of the differences. This could be addressed by assessing MVC at the end of the experimental trials and comparing this numbuer with the pre- test MVC.

Findings from this study can be used to drive new studies involving the force level-segment interaction in tasks requiring coordination of multiple digits, including tasks requiring both the same direction of force by both digits or the opposite direction of force by thumb and index finger.  Another application might be in designing new interactive control devices, such as video game controllers or robotic arm manipulators, which require high levels of precise fine motor control.

## Chapter 5: Conclusions

The results this study did not support the first hypothesis, which stated there would be no differences in accuracy or smoothness of task performance among the different force levels. Instead the accuracy for the thumb, index finger, and combined thumb and index finger decreased significantly as force level increased. On the other hand, the smoothness of task performance for all dependent variables increased as force levels increased. Data regarding the second hypothesis, that there would be no differences in accuracy or smoothness of task performance among the various combinations of force application and release, also did not support the null hypotheses for some of the dependent variables. Only for the thumb were there significant differences in accuracy that suggested as force levels increased, accuracy decreased based on the combinations of force application and release. The smoothness of performance based on the combination of force application and release was found significantly different only for the thumb and the combined thumb and index finger variables. Future work is needed to better understand how the thumb and index finger manipulate varying forces at a single maximum force level while dealing with the various combinations of force application and release in different populations and different orders of application and release. This information could be very valuable when assisting with rehabilitation from head injury, neurological disease or stroke as well as maybe one day becoming a diagnostic tool for these all too common problems in today's society.

# Appendix

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Forcelevel | 69.391 | 3 | 23.130 | 34.433 | .000 |
| Segment | 2.579 | 3 | .860 | 1.280 | .281 |
| Forcelevel * Segment | 12.256 | 9 | 1.362 | 2.027 | .036 |

**Appendix A.** 4 (Force Levels) X 4 (Segments) analysis of variance (ANOVA) test for combined thumb and index finger RMSE

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Forcelevel | 1.038 | 3 | .346 | 9.831 | .000 |
| Segment | 1.373 | 3 | .458 | 13.001 | .000 |
| Forcelevel * Segment | .330 | 9 | .037 | 1.043 | .405 |

**Appendix B.** 4 (Force Levels) X 4 (Segments) analysis of variance (ANOVA) test for combined thumb and index finger CVE

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Forcelevel | 42.277 | 3 | 14.092 | 96.156 | .000 |
| Segment | 1.504 | 3 | .501 | 3.422 | .018 |
| Forcelevel * Segment | 2.394 | 9 | .266 | 1.815 | .064 |

**Appendix C.** 4 (Force Levels) X 4 (Segments) analysis of variance (ANOVA) test for thumb RMSE

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Forcelevel | 1.819 | 3 | .606 | 7.795 | .000 |
| Segment | 6.126 | 3 | 2.042 | 26.249 | .000 |
| Forcelevel * Segment | 1.696 | 9 | .188 | 2.423 | .011 |

**Appendix D.** 4 (Force Levels) X 4 (Segments) analysis of variance (ANOVA) test for Thumb CVE

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Forcelevel | 27.217 | 3 | 9.072 | 163.094 | .000 |
| Segment | .195 | 3 | .065 | 1.166 | .323 |
| Forcelevel * Segment | .280 | 9 | .031 | .560 | .829 |

**Appendix E.** 4 (Force Levels) X 4 (Segments) analysis of variance (ANOVA) test for Index Finger RMSE

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| ForceLevel | 1.024 | 3 | .341 | 5.234 | .002 |
| Segment# | .345 | 3 | .115 | 1.765 | .154 |
| ForceLevel * Segment# | .535 | 9 | .059 | .912 | .515 |

**Appendix F.** 4 (Force Levels) X 4 (Segments) analysis of variance (ANOVA) test for Index Finger CVE

## References


Danion F. & Gallea C. (2004). The relation between force magnitude, force steadiness, and muscle co-contraction in the thumb during precision grip. *Neurosicence Letters*, *368*, 176-180

Francis K.L., Macrae P.G., Spirduso W.W., & Eakin T. (2012). The effects of age on precision pinch force control across five days of practice. *Current Aging Science*, 5, 2-12.

Harbst K.B., Lazarus J.C., & Whitall J. (2000). Accuracy of dynamic isometric force production: The influence of age and bimanual activation patterns. *Motor Control*, *4*, 232–256.

Knight C.A. & Kamen G. (2007). Modulation of motor unit firing rates during a complex sinusoidal force task in young and older adults. *Journal of Applied Physiology, 102*, 122-129.

Lindberg P., Ody C., Feydy A., & Maier M.A. (2009). Precision in isometric precision grip force is reduced in middle-aged adults. *Experimental Brain Research, 193*, 213-224.

Masumoto J. & Inui N. (2010). Control of increasing or decreasing force during periodic isometric movement of the finger. *Human Move Science, 29*, 339-348.

Moerchen V.A., Lazarus J.C., & Gruben K.G. (2007). Task-dependent organization of pinch grip forces. *Experimental Brain Research, 180*, 367-376.

Ranganathan V.K., Siemionov V., Sahqal V., & Yue G.H. (2001). Effects of aging on hand function. *Journal of the American Geriatric Society, 49*, 1478-1484.

Slifkin A.B, & Newell K.M. (2000). Variability and noise in continous force production. *Journal of Motor Behavior*. 32(2), 141-50.

Slobounov S., Johnston J., Chiang H., & Ray W. (2002). Movement-related EEG potentials are force or end-effector dependent: evidence from a multi-finger experiment. *Clinical Neurophysiology, 113*, 1125-1135.

Spirduso W.W., Eakin T., Francis K., & Stanford C. (2005). Quantification of manual force control and tremor. *Journal of Motor Behavior, 37*, 197-210.

Spirduso W.W., and Choi J. (1993). Age and practice effects on force control of the thumb and index fingers in precision pinching and bilateral coordination. In G.E. Stelmach 7 V. Humberg, (Eds) Sensorimotor impairments in the elderly: Are they reversible? (pp. 393-412). Dordrecht, Nederlands: Kluwer Academic Publishers.

Taylor A.M., Christou E.A., & Enoka R.M. (2003). Multiple features of motor-unit activity influence force fluctuations during isometric contractions. *Journal of Neurophysiology*, *90*, 1350-1361.

# Vita

Melissa Marie Lewis graduated from the University of Wisconsin-Green Bay in 2009 with a B.S. in Human Biology. As an undergraduate student, she was a member of the UWGB women's softball team. While at The University of Texas at Austin, she was a teaching assistant for motor learning labs and a student manager for the Texas Longhorns women's softball team. After graduating with her master's degree from The University of Texas at Austin in Kinesiology, she plans to continue her education and obtain a PhD in order to fulfill her dream of a long, successful career in academia and brain injury research.

Email Address: mmlewis@utexas.edu

This thesis was typed by the author.